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The following component part numbers comprise the compilation report:

ADP010398 thru ADP010406

Technologies for Future Precision Strike Missile Systems - Introduction/Overview

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Abstract/Executive Summary

This report documents the results of NATO Research and Technology Organization (RTO) lecture series number 221, entitled "Technologies for Future Precision Strike Missile Systems." The lecture series was conducted under the RTO Consultant and Exchange (C&E) Program as a two-day educational event, first held March 23-24, 2000 in Atlanta Georgia, at the Georgia Institute of Technology. Following the lectures at Georgia Tech, the lectures were held April 3-4 in Turin, Italy and April 6-7 in Ankara, Turkey.

The primary purpose of the lecture series was the disseminating of state-of-the-art scientific and technical knowledge among a wide audience. The lecture series director and three other speakers provided lectures.

Emerging technologies for precision strike missile systems that were addressed in the lecture series included:
Missile aeromechanics technologies. Assessments included hypersonic airframes, low cost/high temperature structure, and ramjet propulsion.
Guidance & control technologies. An overview of existing guidance and control was given. Assessments included precision navigation using light weight/low cost GPS/INS and optimal guidance laws.
Seeker technologies. Assessments included active and passive imaging infrared and radar seekers.
Missile design technologies. An overview of the missile design process was given. Assessments included computer programs and electronic spreadsheets for conceptual design and missile deign criteria.
Missile/aircraft integration technologies. Assessments included high firepower weapon concepts, reduced observables, and insensitive munitions.
Simulation/validation technologies. Assessments included hardware-in-the-loop and design validation.
Automatic target recognition. Assessments included robust algorithms and hardware/algorithm optimization.

Introduction

The last decade has seen increased usage of precision strike missile systems for military strike operations. Moreover, precision strike missiles are expected to have an even larger share of military strike operations in the future. A key contributor to the increased effectiveness of precision strike missiles is the advancement in technology. Examples of system effectiveness improvements include improved missile accuracy, lethality, and adverse weather capability. This lecture series provided insight into the enabling technologies and the state-of-the-art for precision strike missile systems.

The technical program for the lectures consisted of two days. The first day included registration, opening ceremony, an introduction/overview, and lectures on missile aeromechanics technology, guidance & control technology, seeker technology, and missile design technology. Day 2 continued the program with lectures on missile/aircraft integration, simulation/validation, and automatic target recognition technologies. Following the lectures, there was a round-table discussion to address questions and comments from the attendees. The lecture series director provided concluding remarks.

The lecture series director was Mr. Eugene Fleeman of the Georgia Institute of Technology. Other speakers were Mr. Erik Berglund of the Swedish Defense Research Establishment, and Mr. William Licata of the Raytheon Company.

Paper presented at the RTO SCI Lecture Series on "Technologies for Future Precision Strike Missile Systems", held in Atlanta, USA, 23-24 March 2000; Turin, Italy, 3-4 April 2000; Ankara, Turkey, 6-7 April 2000, and published in RTO-EN-13.

Area	Emphasis
Aerodynamics	●
Propulsion	●
Structure / Materials	●
Guidance & Control	●
Seeker	●
Missile Design	●
Missile / Aircraft Integration	●
Simulation / Validation	●
ATR	●
Data Link	●
Cost / Logistics	○
Observables / Survivability	○

● Emphasis ○ Less Emphasis

Figure 1. Emphasis of This Lecture Series Is on Technologies for Precision Strike Missiles.

Figure 1 summarizes the focus of this lecture series. Primary areas of emphasis were technologies in aerodynamics, propulsion, structures/materials, guidance and control, seeker, missile design, missile/aircraft integration, simulation/validation, and automatic target recognition (ATR). Other areas that were addressed, but with lesser emphasis, included missile cost/logistics, reduced observables, and survivability.

This lecture series recognizes that precision strike missiles are different from other flight vehicles, such as combat aircraft. Precision strike missiles are a technical specialty in their own right. For example, Figure 2 compares precision strike missile characteristics and the current state-of-the-art (SOTA) with that of fighter aircraft. Examples are shown where missiles are driving technology. Also shown are other areas where the missile is not driving technology in comparison with fighter aircraft.

As an example, the lateral and longitudinal acceleration SOTA of missiles exceeds that of combat aircraft. Missile lateral maneuverability of 30+ g's and longitudinal acceleration of 30+ g's have been demonstrated. Notable examples of precision strike missiles with high acceleration and maneuverability include AGM-88 HARM and AGM-114 Hellfire missiles. Missile speed is also usually greater than that of combat aircraft, an example is the AS-17/Kh 31 hypersonic ramjet missile. Another difference is dynamic pressure loading on a missile, which is usually greater than of combat aircraft. An example of a precision strike missile that operates at high dynamic pressure is the ANS ramjet missile. Another difference is the relatively small size and lighter weight of missiles in comparison to combat aircraft, notably the LOCAAS powered submunition. Related to cost, missiles are a throw-away. As a result, they are more cost-driven than combat aircraft.

Precision Strike Missile Characteristics	Example of State-of-the-Art	Comparison With Fighter Aircraft
Acceleration	AGM-88	●
Maneuverability	AGM-114	●
Speed	AS-17 / Kh-31	●
Dynamic pressure	ANS	●
Size	LOCAAS	●
Weight	LOCAAS	●
Production cost	GBU-31	●
Observables	AGM-129	◒
Range	AGM-86	-
Kills per use	Apache	-
Target acquisition	LOCAAS	-

● Superior ◒ Better ○ Comparable - Inferior

Figure 2. Air-Launched Precision Strike Missiles are Different from Fighter Aircraft.

Development cost is smaller for missiles and the difference in production cost is even more dramatic. An example is the GBU-31 JDAM, with cost on the order of $10,000, compared to 10's of millions of dollars for typical combat aircraft. Finally, cruise missiles such as AGM-129 are able to achieve low radar cross section without the other design limitations associated with piloted aircraft.

Areas where the combat aircraft have superior capability include range, targets killed per use, and target acquisition. Although the conventional version of the AGM 86 cruise missile (CALCM) has a flight range that can exceed 1,000 nautical miles, combat aircraft have much longer range. In the area of target kill capability, precision strike missiles have become more efficient in recent years, with a single target kill probability approaching one and a capability for multiple target kills. The Apache missile is an example of an efficient precision strike missile. It has high accuracy and is capable of dispensing submunitions, exhibiting high firepower. However the same missiles are load-outs on combat aircraft, and so the enhancement in missiles also enhances the combat aircraft effectiveness and firepower. Finally, although smart, powered submunitions such as LOCAAS have demonstrated a capability for automatic target recognition (ATR), combat aircraft with a human pilot continues to have superior capability for target recognition, discrimination and acquisition. Autonomous target acquisition by missiles is a relatively immature technology that will improve in the future with new technologies such as multi-mode and multi-spectral seekers.

One of the greatest strengths of a precision strike missile is a reduction in the number of aircraft sorties required to destroy a target. A historical example is the Thanh Hoa Bridge in Vietnam. For over six years, a total of 871 aircraft sorties dropped unguided bombs, but failed to close the bridge. However, on 13 May 972 only four aircraft sorties using laser-guided munitions resulted in direct hits on the supporting piers, dropping the center span and closing the bridge. Precision strike munitions also reduce aircraft attrition losses and the number of downed/captured pilots. Eleven aircraft were lost using unguided munitions in the 871 sorties mentioned above. No aircraft were lost in the four sorties using precision guided munitions.

Examples of Precision Strike Missiles

Figure 3 shows examples of precision strike missiles, characterized according to the targets they are intended to attack.

In the case of **fixed targets** (which are usually large size and relatively soft), a blast fragmentation or dispensed submunition warhead is usually used. Examples of missiles suitable for fixed surface targets include AGM-154 JSOW, Apache, KEPD-350, BGM-109 Tomahawk, and AGM-142 Have Nap.

Another target category is **radar sites**. Radar sites are also relatively soft, anti-radar homing (ARH) missiles usually use blast fragmentation warheads. Modern ARH missiles include AGM-88 HARM, AS-11 Kilter/Kh-58, ARMAT, AS-12 Kegler/Kh-27, and ALARM.

A third target category is **ship targets**. Ship targets are relatively hard targets and require a kinetic energy penetrating warhead, followed by blast fragmentation after penetration of the hull. Anti-ship missiles include the MM40 Exocet, AS-34 Kormoran, AS-17 Krypton/Kh-34, Sea Eagle, and SS-N-22 Sunburn/3M80.

A fourth target category is **armor targets**. This includes tanks, armored personnel carriers, and other armored combat vehicles. Armor targets are small size and very hard. Typical anti-armor warheads include shape charge warhead, explosively formed penetrator (EFP) warhead, and kinetic energy warhead. Anti-armor missiles include Hellfire/Brimstone, LOCAAS, MGM-140 ATACMS, AGM-65 Maverick, and TRIGAT.

A final category is **buried targets**. Buried targets require a high fineness kinetic energy penetration warhead, followed by blast fragmentation. Buried targets include underground command posts and bunkers. Examples of missiles in this category include CALCM, GBU-28, and GBU-31 JDAM.

Alternatives for Precision Strike

Figure 4 compares an assessment of alternatives in establishing mission requirements for precision strike missiles. The assessment of alternatives includes the approaches that are used today by current systems, as

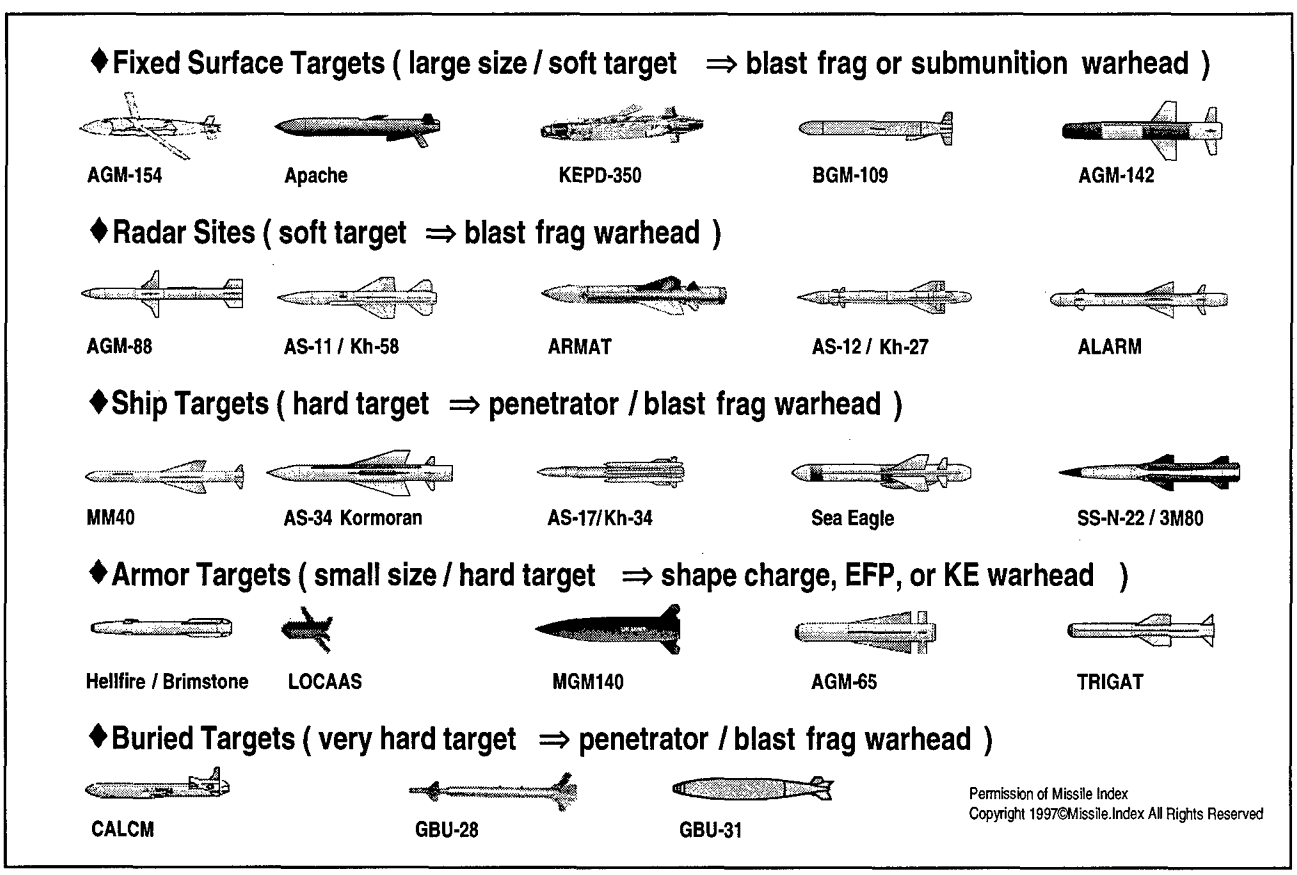


Figure 3. Examples of Precision Strike Missiles.

well as a projection of capabilities that may be used in the foreseeable future for new missile systems. Three measures of merit are shown in comparing future precision strike missiles with current systems. These are cost per shot, number of launch platforms required, and effectiveness against time critical targets. For the current systems, two approaches are used: 1) penetrating aircraft with relatively short range subsonic precision guided munitions and 2) standoff platforms (ships or aircraft) using subsonic cruise missiles. The penetrating aircraft systems include F-117 with subsonic precision guided munitions such as JDAM. As shown in Figure 4, penetrating aircraft/subsonic precision guided munitions have an advantage of low cost per shot. For example, JDAM costs about $10,000. However, the experience in Desert Storm showed a weakness in the capability of penetrating aircraft to counter time critical targets such as theater ballistic missiles (TBMs). Although there were many aircraft on patrol for SCUDs, the aircraft were never in the right place at the right time. Another current approach, using standoff platforms such as ships and large aircraft outside the threat borders requires fewer launch platforms, resulting in lower logistics costs. However, standoff platforms with subsonic cruise missiles (e.g., Tomahawk, CALCM) are also ineffective against time critical targets (TCTs) such as theater ballistic missiles.

Threat TCTs include (1) mobile theater ballistic missile (TBM) launchers, (2) surface-to-air missile (SAM) systems, (3) command, control and communication (C3) sites, (4) storage and support sites for weapons of mass destruction, and (5) other time critical strategic targets such as parked aircraft, bridges and transportation choke points. Mobile TBMs and SAMs are of particular interest. TBMs have short timelines, low signature, and high mobility associated with a "hide-scoot-shoot-scoot-hide" doctrine. Time critical events such as leaving a camouflage/concealment site, moving to a launch site, preparing for launch, tearing down after launch, and moving to a camouflage/concealment site are usually observed too late for current subsonic weapons to provide an effective counter-force response. Stationary dwell time of TBMs may be less than 10 minutes.

Because the location of TCTs is often uncertain or their appearance is sudden, the response capability of current approaches is insufficient. An alternative approach is required.

Figure 4 also shows future missile system alternatives for precision strike. Technology work is under way in all three areas, the most cost-effective approach has yet to be determined. One approach is based on a standoff platform, with an aircraft or ship standing off outside the threat country border. Hypersonic long-range precision strike missiles would provide broad coverage, holding a large portion of the threat country at risk. This approach is attractive in the small number of launch platforms required and the effectiveness against time critical targets. The cost of future hypersonic missiles is expected to be comparable to that of the current cruise missiles, such as Tomahawk.

Alternatives for Precision Strike	Cost per Shot	Number of Launch Platforms Required	TCT Effectiveness
Future Systems			
◆ Standoff platforms / hypersonic missiles	○	●	◒
◆ Overhead loitering UCAVs / hypersonic missiles	◒	◒	●
◆ Overhead loitering UCAVs / subsonic PGMs	●	○	◒
Current Systems			
◆ Penetrating aircraft / subsonic PGMs	●	–	–
◆ Standoff platforms / subsonic missiles	○	●	–

Note: ● Superior ◒ Good ○ Average – Poor

Note: C4ISR targeting state-of-the-art for year 2010 projected to provide 2 minutes target – shooter connectivity and target location error (TLE) less than 1 meter.

Figure 4. Projected Future Capability of Precision Strike Missile Systems.

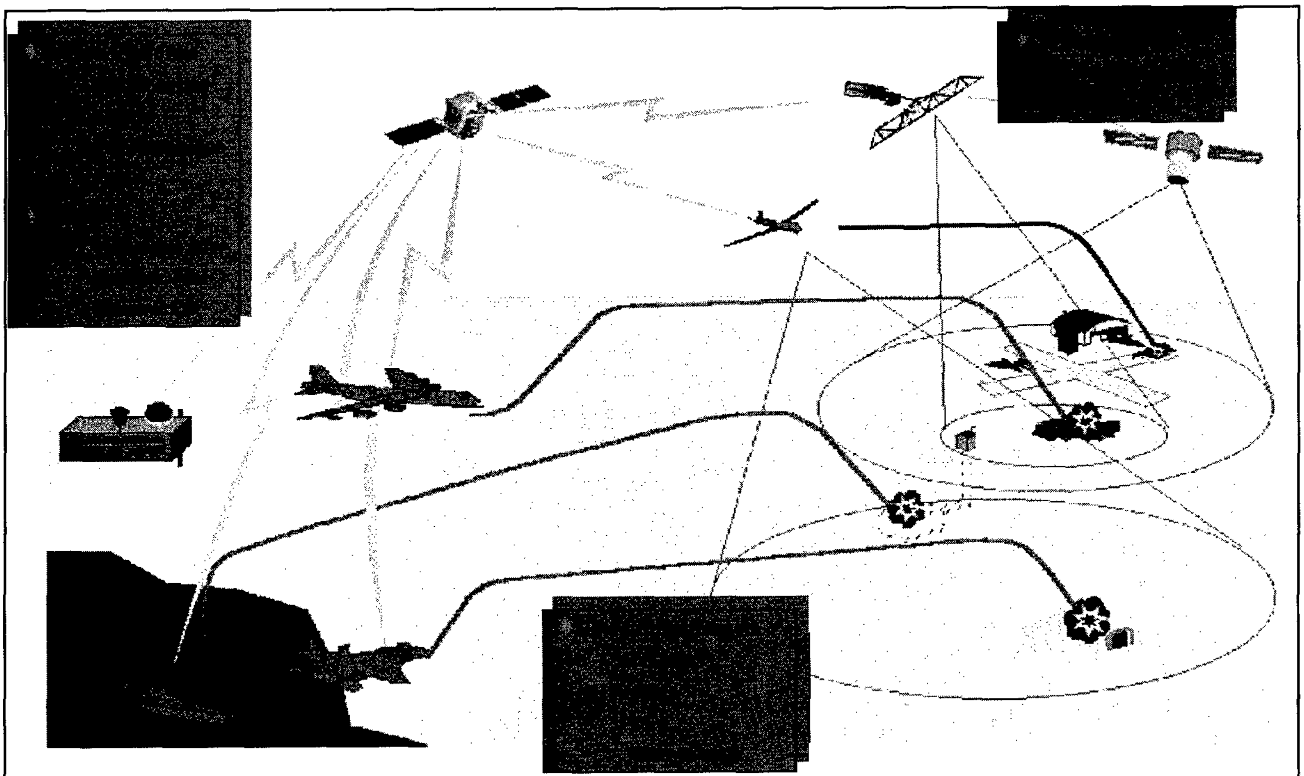
Another alternative approach is to use overhead loitering unmanned combat air vehicles (UCAVs) with hypersonic missiles. The number of UCAVs required is dependent upon the speed and range of their on-board precision strike missiles. This approach would probably provide the fastest response time against time critical targets, because of the shorter required missile flight range for an overhead loitering system.

A third approach is overhead, loitering UCAVs with subsonic precision guided munitions. This approach would have the lowest cost per shot, but would also require a relatively large number of UCAVs.

An enabling synergistic capability for precision strike is the application of near real time, accurate targeting from either overhead tactical satellite or overhead unmanned air vehicle (UAV) sensors. It is expected that an advanced command, control, communication, computers, intelligence, surveillance, reconnaissance (C4ISR) network will be available in the year 2010 time frame to support near-real-time and high accuracy targeting of time critical targets. Figure 5 illustrates an example of a ground station, overhead satellite sensors and satellite relays, and overhead UAV sensor platform elements of the C4ISR architecture. The assumed C4ISR of the year 2010 is projected to have a capability for a target location error (TLE) of less than 1 meter (1 sigma) and sensor-to-shooter connectivity time of less than 2 minutes (1 sigma).

The improved responsiveness of hypersonic precision strike missiles must be harmonized with other measures of merit such as robustness, warhead lethality, miss distance, observables, survivability, reliability, and cost, as well as constraints such as launch platform integration and firepower requirements (Figure 6).

Figure 7 summarizes the technology development and design validation process for precision strike missile systems. The technology development is focussed on the key enabling technologies that are driven by the requirements, but are in need of additional development and demonstration for a required level of maturity. The technology development addresses alternative approaches, risk mitigation, exit criteria for each phase, and an exit plan in the event of failure. The technology development and demonstration activities lead to a level of readiness for entry into Engineering and Manufacturing Development (EMD).



Note: C4ISR targeting state-of-the-art for year 2010 projected to provide 2 minutes target – shooter connectivity and target location error (TLE) less than 1 meter.

Figure 5. Future C4ISR Tactical Satellites and UAVs Will Provide Targeting Against Time Critical Targets.

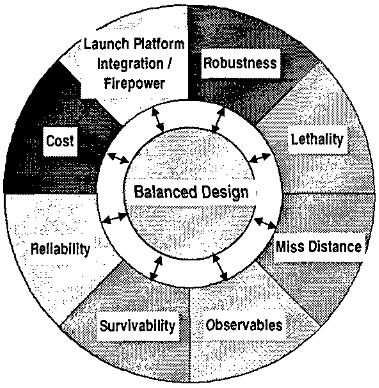


Figure 6. Measures of Merit and Launch Platform Integration Should Be Harmonized.

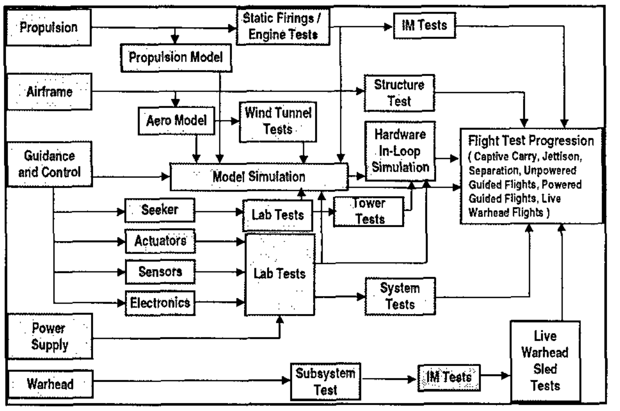


Figure 7. Design Validation/Technology Integration Is An Integrated Process.

Early technology work addresses laboratory tests and demonstrations of critical components in a representative environment, but not necessarily a full-scale environment. The next step of technology development is a laboratory or flight demonstration of a full-scale component in a full-scale environment. This is followed by either a laboratory demonstration or a flight Advanced Technology Demonstration (ATD) of a full-scale subsystem in a full-scale environment of the Concept Definition Phase. Finally, there is a flight demonstration, based on either an Advanced Concept Technology Demonstration (ACTD) or a full-scale prototype in a full-scale environment. This is required for a precision strike missile to enter into EMD.

A primary tool in the design validation/development process is missile system simulation. Initial simulations used in conceptual and preliminary design are digital simulations. As missile guidance & control hardware becomes available, a hardware-in-loop (HWL) simulation is also developed. The HWL simulation incorporates missile guidance & control hardware (e.g., seeker, gyros, accelerometers, actuators, autopilot). It also includes a simulated target signal for the seeker to track. Hybrid computers are used in HWL simulation. Fast analog computers simulate the rapidly changing parameters, such as the flight trajectory. Digital computers simulate the more slowly changing parameters, such as the forces and moments from aerodynamics and propulsion. HWL and digital simulations are the primary system analysis tools used during missile flight tests. For example, simulation results based on wind tunnel data are validated with flight test results. HWL and digital simulations are also used to determine the cause of flight test anomalies.

New Technologies for Precision Strike Missiles

Figure 8 summarizes new technologies for precision strike missiles. Most of these were covered in this lecture series, however there was insufficient time to address them in detail. Almost all subsystems in precision strike missiles are expected to have major technology improvements in the future. The following is an assessment of new technologies for precision strike missiles, following the format of Figure 8.

Dome. New seeker/sensor dome technologies include faceted/window, multi-spectral, and multi-lens domes.

Faceted domes are pyramidal-shaped domes that have reduced dome error slope, resulting in improved guidance accuracy. Seeker tracking errors due to the error slope of a traditional high fineness dome are a problem for imaging infrared and radar seekers. Small changes in the curvature of a dome greatly affect the tracking accuracy. An approach that alleviates the problem, previously developed for the Mistral and SA-16 missiles, is a faceted dome. The SLAM ER precision strike missile and ballistic missile defense interceptors also use a similar approach, based on a single flat window. A faceted dome behaves in the same optical manner as a flat window dome, with an advantage of a wider field of regard available to the seeker. The error slope of a faceted/window dome is nearly negligible compared to a traditional high fineness dome. Another advantage of a flat window is reduced observables. A grid or slotted film over the window can be tuned for transmission in the wavelength or frequency of interest. This results in reduced radar scatter, providing reduced radar cross section (RCS) for the precision strike missile.

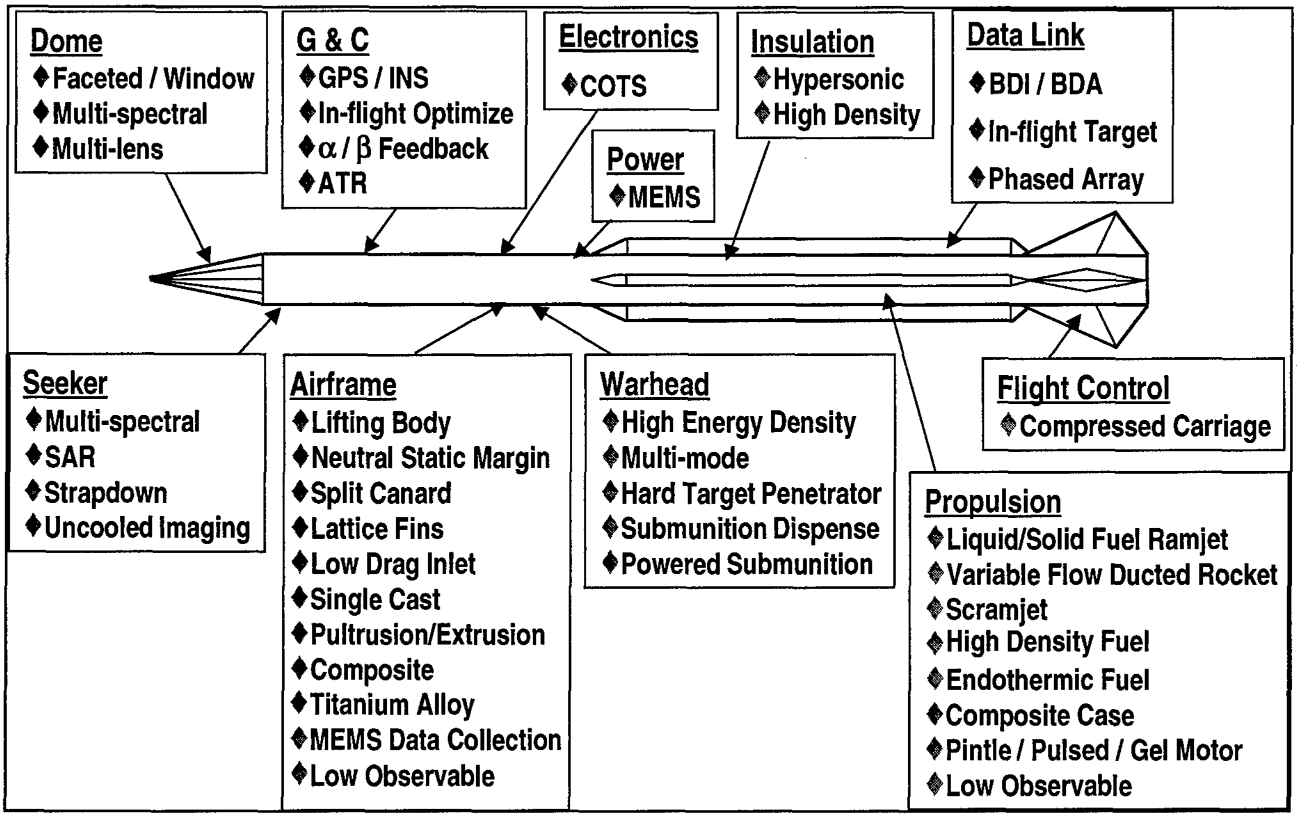


Figure 8. New Technologies for Precision Strike Missiles.

Another dome technology is multi-spectral domes. Multi-spectral domes allow multi-spectral (e.g., mid-wave IR/long wave IR) and multi-mode (e.g., IR/millimeter wave) seekers.

Multi-lens domes are concentric high fineness domes that provide optical correction, resulting in low dome error slope. A high fineness multi-lens dome has lower drag at supersonic speed than a traditional hemispherical dome.

Seeker. New seeker technologies include multi-spectral, synthetic aperture radar (SAR), strapdown, and uncooled IR seekers.

Multi-spectral/multi-mode seekers provide enhanced performance for automatic target recognition. As an example, imaging IR focal plane array (FPA) detectors have the capability to sample multiple wavelengths, providing multi-spectral target discrimination across a broad wavelength. Multi-spectral seekers also have enhanced rejection of false targets and ground clutter.

SAR seekers have good effectiveness in adverse weather and ground clutter. SAR seekers have the flexibility to cover a broad area search (e.g., 5 km by 5 km) for single-cell target detection, then switch to high resolution (e.g., 0.3 meter) for target identification and targeting in ground clutter. An example of a SAR sensor is the Predator UAV TESAR. SAR seekers can also provide high-accuracy profiling of the known terrain features around the target and derive the GPS coordinates of the target.

Strapdown seekers are seekers without gimbals, using electronic stabilization and tracking. The reduction in parts count by eliminating gimbals reduces the seeker cost, which may be the highest cost subsystem of a precision strike missile.

Uncooled IR seekers use an uncooled detector, such as a bolometer. Elimination of a cooling system reduces seeker cost.

G&C. Guidance & control technologies include Global Positioning System/Inertial Navigation System (GPS/INS), in-flight guidance optimization, derived angle-of-attack and angle-of-sideslip feedback for bank-to-turn missiles, and automatic target recognition.

GPS/INS of the year 2010 is projected to have a precision guidance capability of less than 3 meters circular error probable (CEP). GPS/INS precision accuracy permits a low cost seeker-less missile to be used against fixed targets.

INS sensors that cost about $20,000 US a decade ago are now a third of the price. The potential exists for a $2,000 to $3,000 INS, based on Micro-machined Electro-Mechanical Systems (MEMS) technology. MEMS devices are fabricated from a single piece of silicon by semiconductor manufacturing processes, resulting in a small, low-cost package. Between 2,000 and 5,000 MEMS gyro devices can be produced on a single five-inch silicon wafer.

INS sensor alternatives for precision strike missiles include those based on ring laser gyros, fiber optic gyros, digital quartz gyros, and MEMS gyros/accelerometers.

Benefits of GPS/INS integration include higher precision position and velocity measurement, reduced sensor noise, reduced jamming susceptibility, and missile attitude measurement capability. A missile operating at high altitude with a modern GPS receiver will have lower susceptibility to jamming. The availability of GPS to continuously update the inertial system allows the design trades to consider a lower precision and less expensive INS, while maintaining precision navigation accuracy (3 meters CEP) and good anti-jam (A/J) performance.

Modern GPS/INS receivers are based on a centralized Kalman filter that processes the raw data from all of the sensors (e.g., SAR, GPS receiver, INS). GPS/INS Kalman filters with more than 70 states have been demonstrated for precision strike missiles. In addition to enhanced accuracy, Kalman filters also provide robustness against jamming and the loss of satellites. Pseudo-range measurements can be made from three, two, or even one satellite if one or more of the satellites are lost.

Using in-flight digital trajectory flight prediction and derived flight conditions (e.g., Mach number, angle of-attack, angle-of-sideslip, dynamic pressure) from the GPS/INS, the missile can continuously optimize the flight trajectory to maximize performance parameters such as range, off-boresight, and accuracy.

Automatic target recognition will continue to improve as a technology, relieving the workload of the pilot. Advancements in sensor capability for C4ISR will provide new capabilities of near real-time ATR, lower false alarm rate, improved targeting accuracy, and improved data rate.

Electronics. Referring to Figure 8, a fourth area of enabling capability is electronics technology. Revolutionary advancements have been made in high performance, low cost commercial off-the-shelf (COTS) processors. This is an enabling technology for guidance & control and sensor data fusion. The capability to process multi-dimensional discrimination in a low cost, small size, and low power package is beginning to emerge. Processing capability has been doubling about every two years, expanding from 2,300 transistors on the 4004 chip in 1972 to 5.5 million transistors on the Pentium Pro chip in 1995. There is no sign that the growth rate will slow down. A projection to the year 2010 predicts a capability of over 1 billion transistors on a chip. Processing capability is ceasing to be a limitation for the application of sensor data fusion and near real-time trajectory optimization to precision strike missiles.

Airframe. Airframe technologies are enhancing flight performance, reducing weight, permitting higher flight Mach number, reducing cost, providing higher reliability, and reducing observables. Airframe technologies for precision strike missiles include non-axisymmetric lifting bodies, neutral static margin, split canard, lattice fins, low drag inlets, single cast structures, pultrusion/extrusion manufacturing, composites, titanium alloys, MEMS data collection, and low observables.

Lifting body airframes provide enhanced maneuverability and aerodynamic efficiency (lift-to-drag ratio). Enhancements in maneuver and cruise performance are also provided by neutral static margin. Split canard control also provides enhanced maneuverability. Another airframe technology that has high payoff for supersonic precision strike missiles is lattice fins. Lattice fins have advantages of smaller hinge moment and higher control effectiveness. Another airframe technology is low drag inlets. Low drag inlets are in development for hypersonic missiles.

New airframe technology will also reduce the cost of precision strike weapons. Examples of recent precision strike weapons that include low cost technologies include JDAM and JASSM. Technologies to reduce cost are also being introduced into existing weapons, with large savings. An example is Tactical Tomahawk. It has a simple low cost airframe with extruded wings that enables the introduction of low cost commercial parts for G&C and propulsion. The current Tomahawk has 11,500 parts, 2,500 fasteners, 45 circuit cards, 160 connectors, and 610 assembly/test hours. Tactical Tomahawk will have 35% fewer parts, 68% fewer fasteners, 51% fewer circuit cards, 72% fewer connectors, and 68% fewer assembly/test hours – resulting in a 50% reduction in cost. The Tactical Tomahawk also has superior flexibility (e.g., shorter mission planning time, a capability for in-flight targeting, a capability for battle damage indication/battle damage assessment, modular payload) and higher reliability. Tactical Tomahawk demonstrates that reduced parts count is an important contributor to reducing missile cost. The traditional approach to estimating missile unit production cost has been to base the cost estimate on missile weight. However, Tactical Tomahawk is the same weight as the current Tomahawk, at 50% of the cost.

Precision castings will become more prevalent in precision strike missiles. Castings reduce the parts count, with a resulting cost savings. This technology is particularly important to air breathing missiles such as ramjets, which have a more complex nonaxisymmetric shape. Ramjets have traditionally been more expensive than axisymmetric rocket powered missiles. A one-piece cast airframe design integrates all of the secondary structure to minimize the structure parts count. Precision tooling minimizes subsequent machine and hand finishing of mating surfaces, by achieving a precision surface finish "as-cast." Fuel cells can be an integral part of the structure and not require bladders. Structural attachment points (e.g., ejector attachments, payload supports, booster attachments) and self-indexing/aligning features can be integral to the structure. This minimizes or eliminates mating, alignment, and assembly tooling and test (inspection) requirements. Precision castings have been demonstrated for missile aluminum, titanium, and steel airframes, motor cases, and combustors. Ceramic tooling is an enabling technology for low cost precision castings.

Other manufacturing technologies that reduce airframe cost include pultrusion and extrusion manufacturing of the missile structure.

Composite materials will find increased use in new missile airframe structure. High temperature composites particularly have benefits for hypersonic missiles, which require weight reduction. Another technology is titanium alloys. Titanium alloy technology enables lighter weight missiles for a hypersonic, high temperature flight environment.

Future precision strike missiles will have low cost/small size MEMS sensors for data collection during missile development and for health monitoring after production. Localized stress, temperature, and other environmental conditions can be monitored through many sensors scattered around the airframe.

Finally, the airframe shaping and materials technology development for low observable cruise missiles will provide future reduction in observables.

Power. Power supply technology is also expected to benefit from the application of MEMS. The energy per weight available from a MEMS power system is much greater than that of thermal batteries. Micro turbine generator technology is based on micro-machined semiconductor manufacturing techniques. It is basically a miniature generator that is powered by a miniature jet engine. A micro turbine generator offers a greater than 15 to 20 times weight and volume advantage.

Warhead. Enhanced warhead technologies for precision strike missiles include high energy density warheads, multi-mode warheads, hard target penetrator warheads, submunition dispense, and powered submunitions.

Current high explosive warheads have cross-linked double base (XLDB) explosive charges such as HMX and RDX. An example of a new high explosive charge is the US Navy China Lake CL-20. CL-20 is chemically related to current XLDB nitramine explosives. However, CL-20 is a cyclic polynitramine, with a unique caged structure that provides higher crystal density, heat of formation, and oxidizer-to-fuel ratio. CL-20 propellant has 10-20% higher performance than HMX and RDX. CL-20 also has reduced shock sensitivity (class 1.3 versus 1.1) and milder cookoff reaction than either HMX or RDX.

There is emphasis to reduce unit production cost and logistics cost by producing a multipurpose missile that covers a broader range of targets. An example is the Joint Standoff Weapon (JSOW). JSOW is a neck-down replacement of Walleye, Skipper, Rockeye, Maverick, and laser guided bombs. A multipurpose weapon system for precision strike is inherently flexible because it can engage a broader target set. A modular warhead provides enhanced capability to engage and defeat hardened, buried targets, and mobile surface targets.

Warheads for penetrating deeply buried targets are based on a kinetic energy penetration warhead case that includes a small explosive charge. The technology for kinetic energy penetrator warhead includes penetrator shape, case material, explosive, and fuze to survive and function at high deceleration.

Submunition dispense and powered autonomous submunitions such as LOCAAS have the capability to counter mobile, time critical targets such as TBMs. A powered submunition can search a relatively large area, providing the potential for locating a TBM launcher after the launch site has been vacated. This provides robustness against uncertainties in the time lines for C4I and target dwell. A technical challenge is supersonic/hypersonic dispense of submunitions. The flight environment of high dynamic pressure and shock wave-boundary layer interaction is relatively unexplored. Aft dispense of submunitions is an enabling technology for supersonic/hypersonic submunition dispense.

Insulation. Referring again to Figure 8, an eighth area of enabling capability is insulation technology. Higher density external airframe and internal insulation materials are in development for hypersonic missiles. Most precision strike missiles are volume-limited rather than weight limited. Higher density insulation materials permit more fuel/propellant, resulting in longer range.

Propulsion. Emerging propulsion technologies include liquid/solid fuel ramjet, variable flow ducted rocket, scramjet, high density fuel, endothermic fuel, composite motor case, rocket motor energy management, and low observables.

Turbofan and turbojet propulsion systems are relatively mature technologies for precision strike missiles. They are most suited for subsonic cruise missiles, providing high efficiency to deliver a warhead at long range against non-time-critical targets.

Turbofans/turbojets have an operating regime from Mach 0 to about Mach 3. However, beyond Mach 2, increasingly complex inlet systems are required to match delivered inlet airflow to compressor capacity, and expensive cooling systems are required to avoid exceeding material capabilities at the turbine inlet.

Liquid/solid fuel ramjet propulsion provides high specific impulse for efficient cruise at a Mach number of about 4 and an altitude of about 80,000 feet. Above Mach 5, deceleration of the inlet airflow to subsonic velocity results in chemical dissociation of the air, which absorbs heat and reduces the useful energy output of the combustor. Also, two or more oblique shock compressions are required for efficient inlet pressure recovery at a Mach number greater than 5.0, adding to the complexity, cost, and integration risk of a ramjet missile.

Variable flow ducted rocket propulsion has advantages of higher acceleration than a liquid/solid fuel ramjet and longer range than a solid rocket. For precision strike missions, it is particularly applicable to the suppression of long range, high performance SAMs. The ducted rocket acceleration and fast response to Mach 3+ provides short response time for an anti-SAM engagement. Ducted rockets utilize a gas generator to provide fuel-rich products to the combustor. The fuel-rich products mix and burn with the air from the inlet. The specific impulse of a ducted rocket is between that of a ramjet and a solid rocket.

Supersonic combustion ramjet (scramjet) propulsion is most efficient for cruise Mach numbers 6 or greater. The scramjet maintains supersonic flow throughout the combustor. A technical challenge for the scramjet is fuel mixing and efficient combustion. There are extremely short residence times for supersonic combustion. Another technical challenge is inlet integration for efficient pressure recovery. Like the ramjet, the scramjet is rocket boosted to a supersonic takeover speed. The takeover speed of a scramjet is about Mach 4.5, higher than a ramjet, requiring a larger booster. For a weight-limited system, a scramjet missile will have less available fuel than a ramjet missile. An efficient cruise condition for a scramjet is about Mach 6, 100K feet altitude.

Fuel technologies include high density fuels and endothermic fuels. High density fuels provide high volumetric performance for volume-limited missiles. Endothermic fuels decompose at high temperature into lighter weight molecular products, providing higher specific impulse and permitting shorter combustor length. Endothermic fuels also provide cooling of the adjacent structure.

Another propulsion technology is composite motor cases. Composites provide reduced weight compared to a steel motor case.

Thrust-time history management technologies for rocket motors include pintle, pulsed, and gel propellant motors.

Finally, the emphasis on reduced observable plumes will continue with high emphasis in the foreseeable future.

Data Link. New data link technologies include battle damage indication/battle damage assessment (BDI/BDA), in-flight targeting, and phased array antennas. BDI/BDA can be provided by a data link of target imagery from an imaging IR seeker. In-flight targeting is particularly useful against mobile, time critical targets such as TBMs. Phased array antennas are in development that provide high data rate and flexibility for a precision strike missile to communicate with satellites, ground stations, manned aircraft, and UAVs.

Flight Control. A final area is that of flight control technology for precision strike missiles. The requirement for internal carriage on low observable aircraft has driven new technology in compressed carriage (e.g., small-span/long-chord, folded, wraparound, switchblade) aerodynamic surfaces. This allows higher firepower load-outs for internal carriage on low observable aircraft such as the F-22.